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STUDIES FOR STUDENTS.

THE PRINCIPLES OF ROCK WEATHERING.

(*Concluded.*)

(*c*) MECHANICAL ACTION OF WATER AND OF ICE.

ASIDE from its solvent capacity, water acts as a powerful erosive agent, as well as an agent for the transportation of the eroded materials. It is only its erosive power that need concern us here, though as we shall see this is to a considerable extent dependent upon its power of transportation. Every raindrop beating down upon a surface already sorely tried by heat and frost serves to detach the partially loosened granules, and, catching them up in the temporary rivulets, carries them to the more permanent rills to be spread out over the valley bottoms, or perhaps if the slopes be steep and the current accordingly strong to the rivers and thence to the sea. The amount of detrital matter thus mechanically removed from the hills and spread out over valley and sea bottoms quite exceeds our comprehension, but it is estimated that at the rate the Mississippi River is now doing its work the entire American continent might be reduced to sea level within a period of four and one half million years. The Appalachian Mountain system has already, through this cause, lost more material than the entire mass of that which now remains. But the rivers, like the winds and glaciers, in virtue of this load of sand they bear, become themselves converted into agents of erosion, filing away upon their rocky beds, undermining their banks and continually wearing away the land by their ceaseless activity. The pot-holes in the bed of a stream, formed by the constant swirl of sand and gravel in an eddy, furnish on a small scale striking illustrations of this cutting power, while the rocky canyons of the Colorado of the west, where thousands of feet of horizontal strata have been cut through as with a file,

show the same thing on a scale so gigantic as to be at first scarce comprehensible.¹ An item of no insignificant importance to be considered here, is the possibility, indeed probability, of an incidental chemical decomposition taking place during this abrasive action.

Daubree has shown² that when feldspathic fragments were submitted to artificial trituration in a revolving cylinder containing water, a decomposition was effected whereby the alkalies were liberated in very appreciable amounts. He found further that the principle product of mutual attrition of feldspathic fragments was an impalpable mud (limon) of such tenuity as to remain for many days in suspension, and which on desiccation became so hard as to be broken only with the aid of a hammer, resembling in many respects the argillites of the Coal Measures, but differing in that it carried a high percentage of alkalies. Granitic rocks thus treated yielded angular fragments of quartz and very minute shreds of mica, while the feldspars ultimately quite disappeared in the form of the impalpable mud above mentioned. It was noted that after a certain degree of fineness had been reached further rounding of the particles ceased, owing to the buoyant action of the water, which, in the form of a thin film between adjacent particles, acted as a cushion and prevented actual contact to the extent necessary for mutual abrasion. It is to a similar action on the part of sea water that Shaler³ would attribute the lasting qualities of the sand grains upon our sea beaches. Indeed the conditions of Daubree's experiments as a whole were not so different from those existing in nature that we need hesitate to conclude that similar action, both chemical and physical, may be going on wherever abrasion takes place in the presence of continual moisture, as in the bed of a river or glacier.

The hammering action of the waves upon the seacoast exert

¹ CAPTAIN C. E. DUTTON has estimated (Tertiary History of the Grand Canyon of Colorado) that from over an area of 13,000 to 15,000 square miles drained by the Colorado River an average thickness of 10,000 feet of strata have been removed.

² *Geologie Experimentale*, p. 268.

³ *Bull. Geol. Soc. of America*, Vol. V, p. 208.

a powerful erosive action, particularly upon particles of rock of such size as to be lifted or moved by wave action, but too heavy to be protected from attrition by the thin film of water above alluded to. Shaler's observation¹ at Cape Ann were to the effect that ordinary granitic paving blocks (weighing perhaps twenty pounds) were, when exposed to surf action worn in the course of a year into spheroidal forms such as to indicate an average loss of more than an inch from their peripheries. Experiments made with fragments of hard-burned brick showed that in the course of a year they would be reduced fully one-half their bulk. Even the crystallization of the salt thrown up by wave action and absorbed into the pores of rocks² serves in its way the purposes of disintegration.

The action of freezing water and of ice.—The action of dry heat and cold in disintegrating rocks has already been described. The effects of such temperature changes upon stone of ordinary dryness are however slight in comparison with the destructive agencies of freezing temperatures upon stones saturated with moisture. The expansive force of water passing from the liquid to the solid state has been graphically described as equal to the weight of a column of ice a mile high (about 150 tons to the square foot). Otherwise expressed, one hundred volumes of water expand, on freezing, to form one hundred and nine volumes of ice. Provided then sufficient water be contained within the pores of a stone, it is easy to understand that the results of freezing must be disastrous. That stones as they lie in the ground do contain moisture, often in no inconsiderable amounts, is a fact well-known and well-recognized by all those engaged in quarrying operations, and indeed no mineral substance is absolutely impervious to it. The amount contained naturally varies with the nature of the mineral constituents and their state of aggregation. According to various authorities granite may con-

¹ Bull. Geol. Soc. of America, Vol. V, p. 208.

² According to DANA (Wilkes Exploring Expedition. Geology, p. 529) the sandstones along the coast of Sydney, Australia, are subjected to a mechanical disintegration through the crystallization of the salt which is absorbed from the saline spray of the ocean waves.

tain some 0.37 per cent. by weight; chalk, 20 per cent.; ordinary compact limestone, 0.5 per cent. to 5 per cent.; marble, about 0.30 per cent., and sandstones varying amounts up to 10 or 12 per cent., while clay may contain nearly one-fourth its weight. At and near the surface the amount, particularly after rains, may be very considerably increased. This water is largely interstitial—the *quarry water*, as it is sometimes called. In addition to this the quartz, particularly of granitic rocks, almost universally contains innumerable minute cavities partially filled with water, and which are in extreme cases so abundant as to make up, according to Sorby, at least 5 per cent. of the whole volume of the mineral.

That the passage of this included moisture from the liquid to the solid state may be attended with results disastrous to the stone is self-evident, though the rate of disintegration may be so slow under favorable circumstances as to be scarce noticeable. Freezing of the absorbed water is one of the most fruitful sources of disintegration in stones confined in the walls of a building, and even in the quarry bed it is by no means uncommon to have the material so injured as to render it worthless. However slight may be the effects of a single freezing upon a rock, constant repetition of the process cannot fail to open up new rifts, and still further widen those already in existence, allowing further penetration of water, which freezes in its turn, and exerts a chemical action as well. So year in and year out, through winter's cold and summer's heat, the work goes on until the massive rock becomes loose sand to be caught up by winds or temporary rivulets and spread broadcast over the land. In some instances, it may be, the rock is of sufficiently uniform texture to be affected in all its mass alike. More commonly, however, it is traversed by numerous veins, joints or other lines of weakness along which the rifting power is first made manifest. Naturally disintegration of this kind is confined to frigid and temperate latitudes. As bearing upon the extreme rapidity with which such disintegration may take place, I quote the following from a letter of Dr. L. Stejneger, of the Smithsonian Institution, who passed several months among the islands of Bering Sea:

“In September, 1882, I visited Tolstoi Mys, a precipitous cliff near the southeastern extremity of Bering Island. At the foot of it I found large masses of rock and stone which had evidently fallen down during the year. Most of them were considerably more than six feet in diameter, and showed no trace of disintegration. The following spring, April 1883, when I revisited the place I found that the rocks had split up into innumerable fragments, cube-shaped, sharp-edged, and of a very uniform size, about two inches. They had not yet fallen to pieces, the rocks still retaining their original shape. I may remark, however, that the weather was still freezing when I was there. The winter was not one of great severity and several thawing spells broke its continuity. These cubic fragments did not seem to split up any further, for everywhere on the islands where the rock consisted of the coarse sandstone, as in this place, the talus consisted of these sharp-edged stones.”

Ice acts as an agent of disintegration in still other ways than that mentioned above. Glaciers and their attendant phenomena have, however, been so thoroughly discussed of late in the columns of this and allied journals that my remarks upon the subject may here be very brief. The moving glacier transports more or less rock *débris* fallen upon it from the hills on either hand or picked from the surfaces over which it flows. Those materials which are carried upon the surface, or frozen in the upper portions of its mass, may be but transported to the lower levels, where, the temperature being sufficient, the ice is melted and deposits its load in the form of a moraine. Those which become frozen into the ice-sheet at its under surface are crowded, as the glacier moves onward with all the weight of the overlying mass and all the resistless energy of the ice behind, over the surface of the underlying rocks. In virtue of this material, this sand, gravel and boulder aggregate, the glaciers become converted into what we may compare to extremely coarse files, to tear away the rocks over which they pass and grind and crush them into detritus of varying degrees of fineness. The small streams which originate from the melting of these glaciers become, hence, not

infrequently charged to the point of turbidity with the fine silt-like detritus ground from the ledges and in part from the boulders themselves. This feature has been so frequently noted in geological text-books, as to need no farther mention here.

(d) *Action of plants and animals.*—Both plants and animals aid to some extent in the work of rock degeneration.

The lowest forms of plant life, the lichens and mosses growing upon the hard, bare face of rocky ledges, send their minute rootlets downward into every crack and crevice, seeking not merely foothold but food as well.

Slight as is the action it aids in disintegration. The plants die, and others grow upon their ruins. There accumulates thus, it may be with extreme slowness, a thin film of humus, which serves not merely to retain the moisture of rains but also to bring the rock under the influence of chemical action. As time goes on, sufficient soil gathers for other, larger and higher types of life, which exert still more potent influences. It may be the rock is in a jointed condition. Into these joints each herb, shrub, or sapling pushes down its roots, which in simple virtue of their gain in bulk, day by day, serve to enlarge the rifts and furnish thereby more ready access for water, and the wash of rains to still further augment disintegration. This phase of root action is often well shown in walls of ancient masonry, either of brick or stone, where they greatly accelerate the usual rate of destruction. The depth to which such roots may penetrate has often been noted,¹ varying, as is to be expected with the nature of the soil. In the limestone caverns of the southern states the writer has often noted the number of long thread-like rootlets which have found their way through rifts in the rocky roof, so fine as to be almost imperceptible. In this, as in others of nature's processes, we must remember that nothing is done in haste. With boundless time, and resources without limit, Dame Nature works out her results at her own time and by her own methods.

¹ Aughey has found roots of the buffalo berry (*Shepherdia argophylla*) penetrating the loess soils of Nebraska to the depth of fifty feet.

Aside from this physical action plants promote disintegration by keeping the surface of rocks continually moist, and through their decay by supplying the complex series of compounds commonly called humic, ulmic, crenic and apocrenic acids to which reference has already been made. These act both as deoxidizing and solution agents.

“There is reason to believe that in the decomposition effected by meteoric waters and usually attributed mainly to carbonic acid, the initial stages of attack are due to the powerful solvent capacities of the humus acids. Owing, however, to the facility with which these acids pass into higher states of oxidation, it is chiefly as carbonates that the results of their action are carried down into deeper parts of the crust or brought up to the surface. Although CO_2 is no doubt the final condition into which these unstable organic acids pass, yet during their existence they attack not merely alkalies and alkaline earth, but even dissolve silica.”¹

It is stated by Storer that “on the tops of the higher hills of New Hampshire, and on the coast of Maine also, a cold, sour black earth will often be noticed at the surface of the ground, immediately beneath which is sometimes a layer of remarkably white earth. The whiteness is due to the solvent action of acids that soak out from the black humus, and which leach out from the underlying clay and sand the oxides of iron that formerly colored them, leaving only the insoluble pure clay or sand.”

H. Carrington Bolton has shown that very many minerals are decomposed by the action of cold citric acid for a more or less prolonged period, the zeolites and other hydrous silicates being especially susceptible. Such tests have a peculiar significance when we consider that the roots of growing plants secrete an acid sap

¹ GEIKIE, *Text-book of Geology*, 3d ed., p. 472. The writer was shown not long since, a very practical illustration of the remarkable corrosive power of organic acids. A highly ornate French clock with case of black marble was packed for storage in excelsior which was a trifle damp. The clock remained in storage from the last of May until about the first of October. When the packing material was removed, the marble was found to be so corroded as to need rehoning and polishing. The roughness could be easily felt by passing the finger over the surface, and long lusterless lines indicating the contact of excelsior fibers traversed the surface in every direction.

which by actual experiment has been found capable of etching marble. The exact nature of this acid is not accurately known, but it is considered probable that in the rootlets of each species of plant there exist a considerable variety of organic acids.¹

But the effects of plant growth are not necessarily always destructive; they may exert a conservative or even protective action. In glaciated regions it is often the case that the striated and polished surfaces of the rocks have been preserved only where protected from the disintegrating action of the sun and atmosphere by a thin layer of turf or moss. As a general rule, however, the manifest action of plant growth is to accelerate chemical decomposition, through keeping the surfaces continually moist, and to retard erosion.

Action of bacteria.—The researches of A. Müntz,² Widogradsky, Schlösing and others have shown that bacteria may exercise a very important influence in promoting rock disintegration and decomposition. Their influence in promoting nitrification has been already alluded to. It would appear that while these organisms may secrete and utilize for their sustenance the carbon from the carbonic acid of the atmosphere, as do plants of a higher order, they may also assimilate the carbonate of ammonium, forming from it organic matter and setting free nitric acid. Being of microscopic proportions these organisms penetrate into every little cleft or crevice produced by atmospheric agencies, and throughout long periods of time produce results of no inconsiderable geological significance. The depth below the surface at which such may thrive is presumably but slight, and their period of activity limited to the summer months. They have been found on rocks of widely different character—granites, gneisses, schists, limestones, sandstones and volcanic rocks—and on high mountain peaks as well as on lower levels. The Pic Pourri, or Rotten Peak, in the Lower Pyrenees of southwest-

¹ See Application of Organic Acids to the Examination of Minerals. H. CARINGTON BOLTON, Proc. Am. Assoc. for the Advancement of Science XXXI, 1883. Also Available Mineral Plant Food in Soils. B. DYER, Jour. Chem. Society, March 1894.

² COMPTES RENDUS DE L., Academie des Sciences, CX, 1890, p. 1370.

ern France is composed of friable and superficially decomposed calcareous schists throughout the whole mass of which are found the nitrifying bacteria which are believed to have been instrumental in promoting its characteristic decompositions. The organism acts even upon the most minute fragments, reducing them continually to smaller and smaller sizes. Each fragment loosened from the parent mass is found coated with a film of organic matter thus produced, and the accumulation begun by these apparently insignificant forces is added to by residues of plants of a higher order which come in as soon as food and foothold are provided.

Mr. J. E. Mills,¹ as already noted, lays considerable stress on the decomposing effects of the carbonic acid gas which the ants are "continually pouring" into the upper layers of decomposed material. What the original source of this carbonic acid may have been is not stated, but the natural assumption is that it arises from the decomposing organic matter in their burrows.

Certain species of ants, locally known as saubas, or sauvas, live, according to Branner,² in enormous colonies, burrowing in the earth where they excavate chambers with galleries that radiate and anastomose in every direction, and into which they carry great quantities of leaves. Certain species of termites, the *white ants* of Brazil, are also active promoters in bringing about changes in the structure of the soil, and incidentally accelerating decomposition. The organic matter carried by these creatures into the ground, there to decompose, furnishes organic acids to promote further decay in the material close at hand, and by its downward percolation to attack the still firm rocks at greater depths. Indeed these numerous channels, through affording easy access of air, and surface waters with all their absorbed gases or alkaline salts, may serve indirectly a geological purpose scarcely inferior to that of the joints in massive rocks.

The mechanical agency which has already been referred to as instrumental in bringing about a certain amount of decom-

¹ Am. Geologist, June 1889, p. 351.

² Bull. Geol. Soc. of Am., Vol. VII, 1895.

position in silicate minerals, is greatly augmented when such trituration takes place in connection with organic matter. J. Y. Buchanan has shown¹ that the mud of sea bottoms is being continually passed and repassed through the alimentary canals of marine animals, and that in so doing the mineral matter not merely undergoes a slight amount of comminution and consequent decomposition, but a chemical reduction takes place whereby existing sulphates are converted into sulphides. Such sulphides and the metallic constituents of the silicates and other compounds, particularly those of iron and manganese, would on exposure to sea water become converted into oxides. It is through such agencies that he would account for the presence of sulphur in marine muds, and the variations in color, from shades of red or brown to blue and gray, in the former the iron occurring as oxides, while in the latter it exists as a sulphide. Of course either form may be more or less permanent according as the mud may be devoid of animal life, or protected from oxidizing influences.

3. ANALYSES OF FRESH AND DECOMPOSED ROCKS.

Let us now take into consideration a few common rock types which have undergone a process of degeneration through weathering, and by means of analyses ascertain, so far as possible, the chemical and physical changes which have taken place. In the table below are given, in each case, the results of analyses of fresh and decomposed materials, and the calculated percentage loss of constituents, both as relates to the entire rock, and to the individual constituents. In making these calculations it has been necessary to assume that one of the constituents remains practically constant, in order that it may serve as a basis of comparison. That constituent which has been shown by a large series of analyses to be most constant is, among siliceous crystalline rocks, the alumina, though sometimes it is the iron. Among calcareous rocks it is the silica. In any case,

¹On the Occurrence of Sulphur in Marine Muds. *Proc. Royal Soc. of Edinburgh*, 1890-1.

by selecting as a standard of comparison that of the constituents which has suffered the least through the leaching action of water during the process of degeneration, we may gain by calculations which it is unnecessary to repeat here a series of numbers showing the loss of constituents as given below, and which may safely be accepted as rather under than above the actual figures.

ANALYSES OF FRESH AND DECOMPOSED GNEISS.

Constituents	1 Fresh gneiss	2 Decom- posed gneiss	3 Loss	4 Percentage amount of each constituent saved	5 Percentage amount of each con- stituent lost
Silica.....(SiO_2)	60.69	45.31	31.90	47.55	52.45
Alumina.....(Al_2O_3)	16.89	26.55	0.00	100.00	0.00
Iron sesquioxide...(Fe_2O_3)	9.06	12.18	1.30	85.65	14.35
Lime.....(CaO)	4.44	trace	4.44	0.00	100.00
Magnesia.....(MgO)	1.06	0.40	0.80	25.30	74.70
Potash.....(K_2O)	4.25	1.10	3.55	16.48	83.52
Soda.....(Na_2O)	2.82	0.22	2.68	4.97	95.03
Phosphoric acid...(P_2O_5)	0.25	0.47	0.00	100.00	0.00
Ignition.....(H_2O and C)	0.62	13.75	0.00	100.00	0.00
Total loss.....			44.67		

ANALYSES OF FRESH ELÆOLITE SYENITE AND RESIDUAL KAOLIN.

Constituents	1 Fresh syenite	2 Residual kaolin	3 Loss	4 Percentage amount of each con- stituent saved	5 Percentage amount of each con- stituent lost
Silica.....(SiO_2)	59.96	45.81	37.28	37.82	62.18
Alumina.....(Al_2O_3)	18.92	38.19	0.00	100.00	0.00
Ferric Iron.....(Fe_2O_3)	4.87	1.34	4.19	13.83	86.17
Lime.....(CaO)	1.35	0.33	1.19	12.10	87.90
Magnesia.....(MgO)	0.69	0.25	0.57	17.90	82.10
Potash.....(K_2O)	6.00	0.23	5.90	18.15	81.85
Soda.....(Na_2O)	6.32	0.37	6.15	2.89	97.11
Ignition.....(H_2O)	1.84	13.48	0.00	100.00	0.00
Total loss.....			55.28		

ANALYSES OF FRESH AND DECOMPOSED DIORITE.

Constituents	1 Fresh diorite	2 Decom- posed diorite	3 Loss	4 Percentage amount of each constit- uent saved	5 Percentage amount of each con- stituent lost
Silica(SiO_2)	46.74	42.45	17.43	62.69	37.31
Alumina.....(Al_2O_3)	17.61	25.51	0.00	100.00	0.00
Iron sesquioxide..(Fe_2O_3)	16.79	19.20	3.53	78.97	21.03
Lime(CaO)	9.46	0.37	9.20	2.70	97.30
Magnesia.....(MgO)	5.12	0.21	4.97	2.83	97.17
Potash.....(K_2O)	0.55	0.49	0.21	61.25	38.75
Soda.....(Na_2O)	2.56	0.56	2.17	15.13	84.87
Phosphoric acid ...(P_2O_5)	0.25	0.29	0.05	80.11	19.89
Ignition(C and H_2O)	0.92	10.92	0.00 ¹	100.00	0.00
Total loss.....			37.56		

¹ A gain.

ANALYSES OF FRESH LIMESTONE AND ITS RESIDUAL CLAY.

Constituents	1 Fresh limestone	2 Residual clay	3 Loss	4 Percentage amount of each con- stituent saved	5 Percentage amount of each con- stituent lost
Silica(SiO_2)	4.13	33.69	0.00	100.00	0.00
Alumina(Al_2O_3)	4.19	30.30	0.35	88.65	11.35
Ferric oxide(Fe_2O_3)	2.35	1.99	2.13	10.44	89.56
Manganous oxide ..(MnO)	4.33	14.98	2.49	42.41	57.59
Lime(CaO)	44.79	3.91	44.31	1.07	98.93
Magnesia(MgO)	0.30	0.26	0.26	10.62	89.38
Potash(K_2O)	0.35	0.96	0.23	33.63	66.37
Soda(Na_2O)	0.16	0.61	0.085	46.74	53.26
Water(H_2O)	2.26	10.76	0.95	58.37	41.63
Carbonic acid(CO_2)	34.10	0.00	34.10	0.00	100.00
Phosphoric acid ...(P_2O_5)	3.04	2.54	2.73	10.24	89.76
Total loss			77.635		

In reference to these analyses, it is advisable to make the following statement:

The Virginia gneiss, in the first table, in its fresh condition, as analyzed, is a coarse, gray feldspar, a rich variety, with abundant folia of black mica.

Under the microscope it shows the presence of both potash

and soda-lime feldspars, a sprinkling of apatite and iron ores, sporadic occurrences of an undetermined zeolite, and an extraordinary number of minute zircons, which are mostly included in the feldspars. The residual soil resulting from its decomposition is highly plastic, of a deep red-brown color and has a distinct gritty feeling owing to the presence of quartz and undecomposed silicates. Some 69 per cent. of this soil was found to be soluble in dilute hydrochloric and sodium carbonate solutions. It will be noted that 44.67 per cent. of the original matter has disappeared, and that of the original silica 52.45 per cent. is lost, while 85.65 per cent. of the iron and all the alumina and phosphoric acid remain. All the lime has disappeared; 83.52 per cent. of the potash, 95.03 per cent. of the soda and 74.70 per cent. of the magnesia are likewise missing. The total amount of water has increased very greatly, as was to be expected. The calculation shows a small apparent gain in phosphoric acid, but the amount of this constituent is so slight in the original rock as to render it probable that this is due to errors of analysis.

The elæolite syenite in the second series is a coarsely crystalline granular rock containing orthoclase feldspar in broadly tabular forms, accompanied by nepheline, biotite, pyroxene, titanite and apatite, while fluorite, analcite, and thomsonite, together with calcite, occur as secondary products. The rock weathers away to a coarse gray gravel which ultimately yields a clay from which may be obtained, by washing, a kaolin of a fair degree of purity. The analyses are from the work of J. Francis Williams.¹

The calculations show a much greater loss of silica than in the gneiss, a feature due, as will be noted later, to the absence of free quartz in the syenitic rock. Attention should be called to the fact that the soda has been carried away in greater proportions than the potash.

The diorite in the third series of analyses is, when fresh, a compact fine-grained, almost coal-black rock, sometimes finely speckled with white from the presence of feldspars. The micro-

¹ Ann. Rep. State Geol. Survey of Arkansas, 1890, Volume II.

scope shows it to be composed mainly of hornblende and soda-lime feldspars with interstitial areas of titanite iron. The clay or soil to which it gives rise on decomposing is deep brownish-red in color and highly plastic, though distinctly gritty from the presence of undecomposed feldspars. Though so rich in iron it is to be noted that the residual clay is little if any deeper in color than that from the gneiss. The analysis shows that 37.56 per cent. of the total rock has disappeared.

The limestone of the fourth series is of Carboniferous Age, very impure, crystalline granular, and of a dark chocolate-brown color. The residual clay from its decomposition is a trifle darker, highly plastic and quite impervious. The analyses, calculations, and descriptions are from the work of Penrose.¹

It is to be noted that all that the lime which existed as carbonate, has been entirely removed, as shown by the absence of carbonic its acid in the clay. Farther, that the clay, notwithstanding highly hydrated condition, in reality contains scarcely half the amount of water it would, had the small amount (2.26 per cent.) in the fresh limestone been allowed to accumulate without loss.

DISCUSSION OF RESULTS AND RÉSUMÉ.

Taking now into consideration in connection with these analyses the statements embodied in the first part of this paper relative to the agencies of degeneration, and making due allowance for possible errors in our methods of calculation, there are certain general deductions that may, apparently, be drawn with safety. In the résumé given below, however, reliance is placed not more upon our own analyses than upon results obtained by others as given in existing literature.²

Let us briefly review the subject and make the deductions accordingly.

In glancing over the columns of our analyses it is at once

¹ Ann. Rep. Geol., Survey of Arkansas, 1890, Volume I.

² See especially Roth's *Allgemeine u. Chemische Geologie*, Vol. III, and Ebelman's papers in *Annales des Mines*, Vols. VII, 1845, and XII, 1847.

apparent that hydration is an important factor, the amount of water increasing rapidly, as decomposition advances. There is, moreover, among the siliceous crystalline rocks in every case a loss in silica, a greater proportional loss in lime, magnesia, and the alkalis, and a proportional increase in the amounts of alumina and sometimes of iron oxides, though the apparent gain may in some cases be due to the change in condition from ferrous to ferric oxide. As a whole, however, there is a distinct loss of materials, though the residuary product may actually contain a larger percentage of certain constituents than did the rock from which it was derived.

According to Bischof and as shown in our own work the silicates in any rock that are most readily decomposed are, as a rule, those containing protoxides of iron and manganese, or lime, and the first indication of decomposition is signaled by a ferruginous discoloration and the appearance of calcite.

Fournet, from a study of the processes of kaolinization, was led to state¹ that the hornblende yields less readily to decomposing forces than does feldspar, when the two are associated in the same rock. Becker, however, in studying deep-seated decomposition in the Comstock lode of Nevada, arrived at a precisely opposite conclusion, the feldspars as a whole offering more resistance than the augite, hornblende, or mica.

The present writer has described² thick sheets of augite porphyrite in Gallatin county, Montana, in which the feldspathic disintegration has gone on so far that the mass falls away to a coarse sand, from which still perfectly outlined crystals of coal-black augites may be gleaned in profusion. This last is, however, in a semi-arid region, and the process thus far more one of disintegration than decomposition.

In any climate, minerals consisting chiefly of silicates of alumina and magnesia are less liable to decomposition than those containing iron protoxides, or lime carbonates, for the reason that the first named are not easily affected by carbonic acid.

¹ *Ann. de Chimie et de Physique*, Vol. LV, 1833, p. 240.

² *Bull. U. S. Geol. Survey*, No. 110, 1894.

Indeed it is ordinarily assumed that the silicate of alumina is not at all affected, but the researches of Müller, to which we have referred, seem to disprove this, as do also the calculations made in previous pages. Those silicates which are least liable to atmospheric decomposition are, as it is to be expected, those which have resulted from the alteration of less stable silicates, as serpentine from olivine, epidote from hornblende, or kaolin from feldspar, etc. So much is this so that serpentine has been called a final product of alteration. A few silicates like tourmaline and zircon, or garnet, or oxides like rutile and magnetite, or the salts of rarer earths like monazite, etc., are scarcely at all affected by any of the ordinary products of decomposition, but remain in the form of residual sands in the beds of streams, from whence the lighter, more decomposed, material is removed by erosion.

In the weathering of potash feldspar rocks carrying black mica, the latter mineral is, as a rule, the first to give way, and at times almost wholly disappears. With basic rocks, on the other hand, the dark mica is one of the most enduring of the constituents, and in the residual sands may be found in surprisingly large proportions.

Among the feldspars the potash varieties are, as a rule, far more refractory than the soda lime, or plagioclase, varieties. This is shown not merely by our own investigations, but by those of others as well. Roth shows¹ from analyses of fresh and weathered phonolites, nepheline basalts, and dolorites that the loss of soda is almost invariably greater than that of potash.

Indeed as shown in our analyses the potash feldspars may lose very little by decomposition, but be converted into the condition of fine silt merely through a mechanical splitting up. This fact will in part explain the relative scarcity of free potassium salts (carbonates, sulphates, and nitrates) as compared with those of soda.²

¹ Op. cit., 3d ed., 2d Heft.

² An oligoclase occurring in a tourmaline granite on the southern slope of Mt. Mulatto, near Predazzo, undergoes, according to Lemberg (*Zeit. der deutsch. geol. Gesellschaft*, 28, 1876), a much more rapid decomposition than the orthoclase with which it is associated, and gives rise to a green lusterless serpentine-like product. The

The chemical processes involved in this feldspathic decomposition are of sufficient importance to warrant further discussion, even though it may involve a certain amount of repetition of what has gone before.

Berthier, Forschammer, Brogniart,¹ Fournet,² and others explained more than fifty years ago the process of feldspathic disintegration through the breaking up of its complex molecule into alkaline silicates soluble in water and aluminous silicates which are insoluble. The loss in silica, as noted above, was supposed to be due to the removal, by solution, of these alkaline silicates. Ebelman,³ however, subsequently showed that silicate minerals poor or quite lacking in alkalis lost a portion of their silica with equal facility. He accounted for this on the supposition that the silica set free—in a nascent state—was soluble either in pure water, or water containing carbonic acid. Bischof states that when meteoric waters containing carbonic acid filter through rocks containing alkaline silicates, the first action consists in the partial decomposition of these substances by the carbonic acid, and the formation of alkaline carbonates, which are dissolved.

If the water thus impregnated, on penetrating further below the surface, comes in contact with calcareous silicates, another change will take place consisting of a decomposition and replacement of these calcareous silicates by the alkaline silicates, and a

chemical changes incidental to the alteration are as shown in the following tables, I being the fresh oligoclase and II the decomposition product.

	I.	II.
Silica, - - - - -	59.51	45.29
Alumina, - - - - -	25.10	25.68
Iron sesquioxide, - - - - -	1.08	12.29
Lime, - - - - -	4.03	0.52
Magnesia, - - - - -	trace	2.98
Potash, - - - - -	2.10	3.00
Soda, - - - - -	7.26	2.14
Water, - - - - -	0.92	12.49

¹ Arch du Museum, Vol. I, 1839 (cited by Ebelman).

² Annales de Chimie et de Physique, Vol LV, 1833.

³ Annales des Mines, Vol. VII, 1845.

removal of the lime set free, as a carbonate, provided the water still contains a sufficient amount of carbonic acid. This replacing process and the retention of the alkaline silicates is accounted for on the supposition that, in their nascent state, they form new combinations with the other silicates present, while the lime remains as a carbonate to be removed or not as the case may be. He further states that the alkaline carbonates originating in the manner described are among the most soluble substances known; the carbonate of soda requiring for solution only six times its weight of water at ordinary temperatures. Silica, on the other hand, even in its most soluble form, requires 10,000 times its weight of water for solution. If, therefore, the decomposition of feldspar by such carbonated water were ever so energetic, there would be sufficient water for the solution of the carbonate of soda formed. But if the silica separated meanwhile amounted to more than $\frac{1}{10000}$ of the water present, the excess could not be dissolved, but would remain mixed with the kaolin.

The case is very different when the decomposition of feldspar is effected by fresh water containing only minute quantities of carbonic acid. By the action of such water, only very small quantities of alkaline carbonates are formed; consequently it is possible that the silica separated at the same time, also small in quantity, may find enough water for solution. In such cases the whole of this silica would be removed with the alkaline carbonates, and pure kaolin would be left. Such an action as this does not appear to take place; for the purest of kaolin nearly always contains an admixture of quartz sand or of free silica in some of its forms.

H. P. Murakozy¹ has shown that in the decomposition of rhyolite from Nagy-Mihely, the sanidin passes into kaolin and opal, the latter separating out as hyalite in veins or impure concretionary forms. Through this abstraction of silica there is an apparent proportional increase in the amounts of alumina and alkalis.

It follows from the above considerations that in the decomposition of feldspar into kaolin, more of the silica separated remains

¹ Abstract of F. Becke, Neues Jahrbuch, 1894, 1 Band, 2 Heft, p. 291.

mixed with the kaolin formed, the greater the quantity of carbonic acid in water, and that, perhaps, the amount of carbonic acid in water is never so small that the whole of the silica separated in the decomposition of feldspar can be removed.¹ The above, however, wholly overlooks the possible presence of nitrates, such as we now know from the researches noted on p. 857 must in many cases exist even though in extremely small proportions. It is probable that the small amounts of nitric acid formed by the bacteria would, if not at once taken up by plants, combine immediately with the alkalies, potash, or soda, forming nitrates which, owing to their ready solubility, would be carried away. The larger the proportion of nitric acid, therefore, the greater would be the amount of carbonic left, and consequently the greater would be the amount of silica intermingled with the kaolin, since whatever proportion of the alkalies failed to be carried away as nitrates would pretty certainly disappear as a carbonate. There is also the possibility, especially in the rocks rich in iron protoxides, that a portion of the silica may combine with the iron. (See Bischof, Vol. II, p. 77.)

In cases where the decomposition takes place under the influence of a sufficient supply of oxygen, all iron and presumably the manganese as well would be converted into the insoluble hydrous sesquioxide form and remain with the residue. Where, however, the supply of oxygen is insufficient, a portion or all of these constituents may be removed in the form of protoxide carbonates, or, in the case of iron, as a sulphate.

Reference has already been made to the fact that the magnesia from the decomposition of magnesian silicates was sometimes removed in greater relative portions than was the lime. This seeming anomaly is also sometimes met with in calcareous stratified rocks.

Roth² states that in the weathering of dolomitic limestones the magnesia is often removed in greater proportional quantities than the more soluble lime carbonate.

¹ Chemical and Physical Geology, Gustav Bischof, Vol II, pp. 182, 183.

² Op. cit., Vol. III.

The researches of Hitterman¹ show, however, that carbonic acid solutions *may* exert a scarcely appreciable effect upon magnesian carbonates, which therefore accumulate in the residual soils. In residues derived from limestones this authority also found percentages of alkalis greatly in excess of those in the unchanged rock, indicating beyond a doubt the occurrence of these constituents in the form of insoluble silicates.

It is safe to say that while the general process of rock-weathering may be quite simple, as outlined, there are many minor reactions which it is not possible to describe in detail. It has been shown that even in firm rocks a mutual chemical reaction is not uncommon among minerals lying in close juxtaposition, giving rise to what are known as reaction rims or zones composed of secondary minerals. This is a particularly conspicuous feature in many gabbros where olivine and feldspar are closely adjacent. In these cases a mutual interchange of elements may take place, giving rise to garnets, free quartz or other minerals, as the case may be. This is, to be sure, a deep-seated change, to be classed as alteration rather than decomposition, and taking place presumably under conditions of temperature and solution quite at variance with those existing on the immediate surface. It is, nevertheless, self-evident that when elements are set free through any process, they must almost immediately recombine, taking those forms which existing circumstances may dictate. In a mass of decomposing rock circumstances are almost continually changing, and the inference is fair that new combinations are continually being made and unmade, the intricacies of which we are unable to follow.

Among the siliceous crystalline rocks superficial disintegration is undoubtedly greatly aided by temperature variations which, by rendering the rocks porous, facilitate chemical decomposition. Such action must, however, be merely superficial, and at considerable depths below the surface the change must be purely chemical. The chief conditions favoring chemical action

¹ Die verwitterungse Produkte von Gesteinen der Triasformation Frankr. Inaug. Dissertation. Munich, 1889.

are those of continual percolation by waters carrying the organic acids already described. It naturally follows therefore that a purely chemical decay will progress more rapidly where the rock-mass is covered by such a layer of vegetable soil as shall give rise to the decomposing solutions. Hence, that such an accumulation having begun decomposition will keep on at an ever increasing rate to a depth concerning which we have at present no data for calculation. It must not be too hastily assumed from this that rocks thus protected do in reality disintegrate more rapidly than those exposed on bare hillsides, since here, where physical causes predominate, the loosened particles are removed as fast as formed, and, besides leaving no measure of the destruction going steadily on, new surfaces for attack are being continually exposed. Moreover, in assuming that rocks decay rapidly where covered by vegetation we must not overlook the fact that the character of the overlying soil may be such as to be protective rather than otherwise. Thus, in glaciated regions it is a well-known fact that the striæ on rock surfaces are found best preserved where they have been protected from heat and frost by a mantle of drift, or the compact turf so characteristic of the northern states.

The principles involved in the decomposition of fragmental and stratified rocks are not so different from those we have been discussing as to call for detailed consideration. It is well to note, however, that the materials composing rocks of this type are themselves a product of these very disintegrating and decomposing agencies, but which have become consolidated into rock-masses, and now, once more in the infinite cycle of change, are undergoing a breaking up. It follows from the very nature of the case that such rocks, with the exception of the purely calcareous varieties, will undergo less chemical change than do those we have been discussing. Their feldspathic and easily decomposable silicate constituents long ago yielded to the decomposing processes, and were largely or in part removed before consolidation took place. Thus most sandstones are composed largely of quartzose sand, the least soluble and least changeable product, it

may be, of many a previous disintegration. Hence, the processes involved in the disintegration of the sandstones, shales and argillites are mainly mechanical, with the exception of those which carry a feldspathic or calcareous cement.

It is, however, quite different with the calcareous members of the group, where, with the exception of the granular-crystalline varieties, the process is almost wholly chemical, and notable for its simplicity. In these latter forms, as the saccharoidal marbles, expansion and contraction, from ordinary temperature variations, bring about a more or less rapid disintegration. The decomposition is, however, due mainly to the action of meteoric waters trickling over the surface, or filtering through cracks and crevices under ordinary conditions of atmospheric pressure and atmospheric temperature. Hence, the process is one of superficial solution, and the incidental chemical processes set in motion, as in the feldspar-bearing rocks, are almost entirely lacking. It follows that only the lime carbonate is removed in appreciable quantities, while the less soluble impurities are left to accumulate in the form of ferruginous clays, admixed with quartzose particles, chert nodules, etc. Since in many limestones the amount of these constituents is reduced to a minimum, even, perhaps, to the fraction of 1 per cent., so it happens that hundreds or even thousands of feet of strata may be removed without leaving more than a very thin coating of soil in its place.

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